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Low temperature heating and high temperature cooling systems (water-based radiant heating/cooling systems) are efficient means to heat/cool the buildings. It is possible to further increase the performance of different indoor terminal devices (including radiant systems) by the results obtained from different analysis methods, namely, energy, exergy, and entransy

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Buildings play a key role for the energy efficiency and energy savings in the society level due to their high energy intensity and high energy consumption. Due to these reasons, they also play a key role within the 20-20-20 goals of the European Union.

HVAC systems constitute a high share of the energy consumption in buildings however it is not possible to fully achieve the desired levels of indoor environment quality in a building without HVAC systems.

The main purpose of the HVAC systems is to provide a comfortable, healthy, and productive indoor environment for the occupants however this should be achieved with the lowest possible energy consumption.

Low temperature heating and high temperature cooling systems (water-based radiant heating/cooling systems) emerge as an effective means of achieving both aims due to their significant advantages such as providing uniform temperature distribution in spaces, enabling the integration of renewable energy sources into the HVAC systems, enabling the boiler and chillers to operate at higher efficiencies and so forth (Olesen, 2008), (Olesen, 2002).

Different evaluation methods (energy, exergy and entransy) are available in order to evaluate the performance of different components and the entire HVAC system.

Evaluation methods

During the design, testing and operation phases of the HVAC systems, there is a need to have accurate and precise analysis methods, in order to evaluate the energy performance, to improve the energy efficiency and to quantify the energy and emission saving potentials. Different analysis methods provide different insights to the system under consideration.

Energy and exergy analyses have been applied to buildings, and to larger systems, for example, the European Energy Performance of Buildings Directive (EPBD) uses primary energy or CO2 emission to evaluate energy efficiency and International Energy Agency (IEA), Energy Conservation in Buildings and Community Systems (ECBCS) Annex 37 (Low Exergy Systems for Heating and Cooling in Buildings) and Annex 49 (Low Exergy Systems for High-Performance Buildings and Communities) have worked with exergy as a measure of energy efficiency.

The previously mentioned analysis tools have some limitations. The energy analysis fails to capture the "quality" of energy therefore exergy emerged as a concept that distinguishes between different energy sources based on their potential to do work. However, depending on the definition of the system boundaries, most of the heat transfer processes in a building do not involve heat-to-work conversion.

Electrical charge stored in capacitor Q_{ve} [C]	Electrical current (charge flux) I $[C]/[s] = [A]$	Electrical resistance R_e [Ω]	Capacitance $C_e = Q_{ve}/U_e$ [F]
Heat stored in a body $Q_{vh} = Mc_vT$ [J]	Heat flow $\dot{Q}_h$ [J/s]	Thermal resistance R_h [s K/J]	Heat capacity $C_h = Q_{vh}/T$ [J/K]
Electrical potential U_e [V]	Electrical current density $\dot{q}_e$ $[C/m^2 s]$	Ohm's law $\dot{q}_e = -K_e \frac{dU_e}{dn}$	Electrical potential energy in a capacitor $E_e = \frac{1}{2}Q_eU_e$ [J]
Thermal potential (temperature) $U_h = T$ [K]	Heat flux density $\dot{q}_h$ $[J/m^2 s]$	Fourier law $\dot{q}_h = -K_h \frac{dU_h}{dn}$	?

Figure 1: The analogy between the parameters of electrical and heat conduction (Guo et al., 2007).

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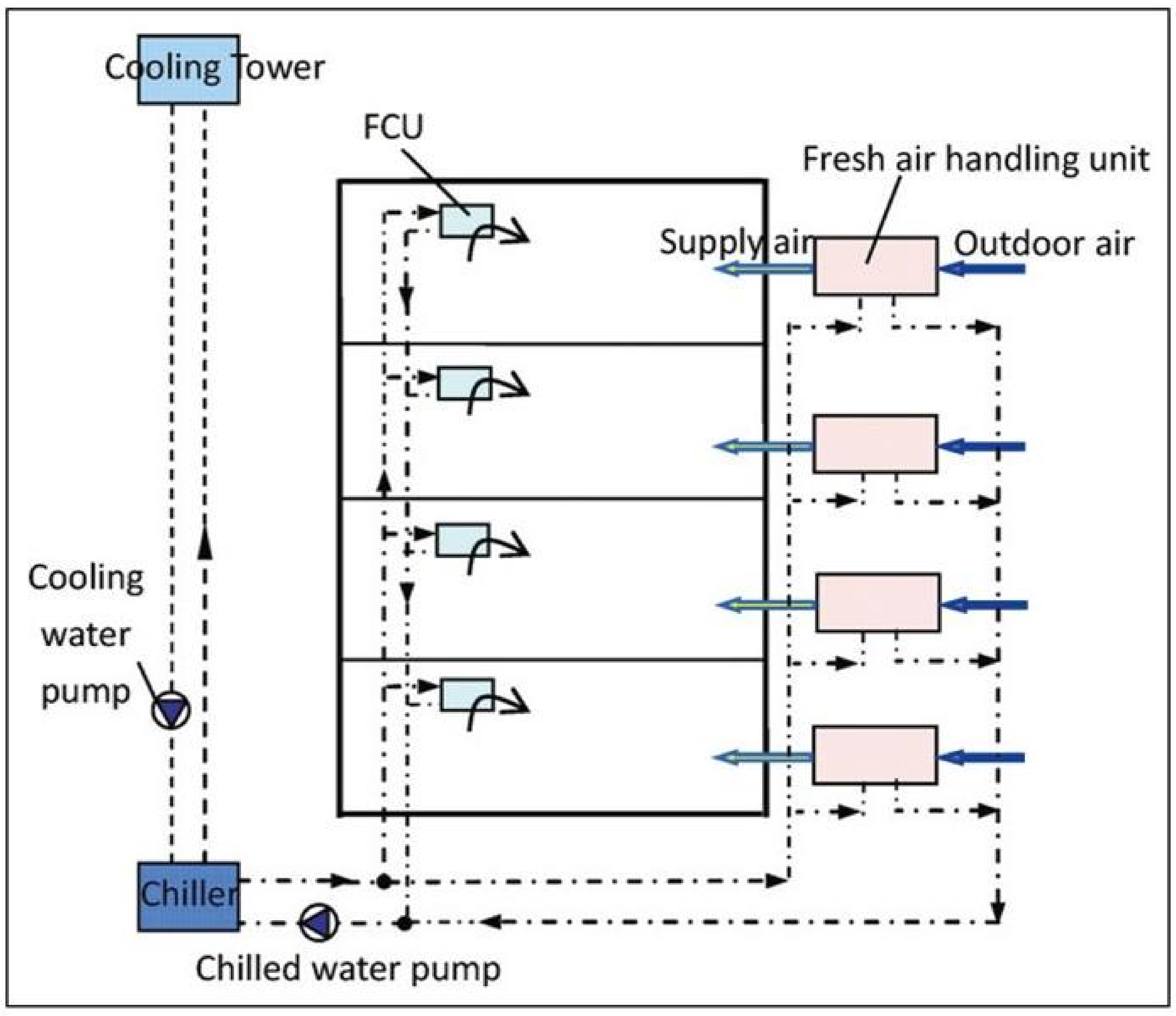

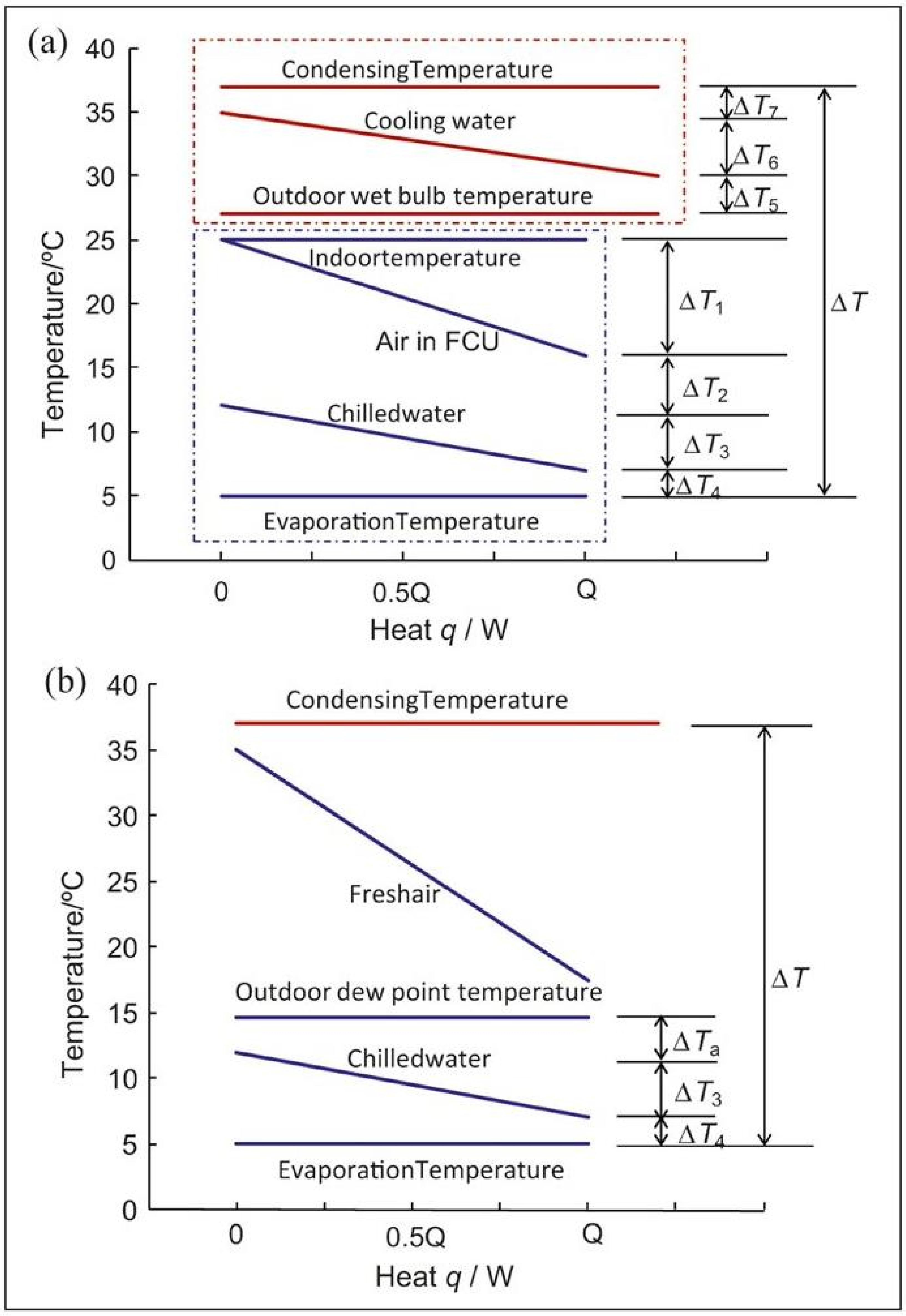

Figure 2: Example of a T-Q diagram for a fan-coil unit and a fresh air handling unit (Zhang et al., 2012).

In the recent years, entransy has emerged as a new concept to evaluate heat transfer processes that do not involve heat-to-work conversion. Entransy is described as an object's ability to transfer heat, "potential energy" of heat, in analogy between electrical and heat conduction which can be seen in Figure 1.
According to Guo et al., entransy is described as

$$\frac{1}{2}Q_{vh}T = \frac{1}{2}Mc_vT^2$$

where Qvh is the thermal energy (or the heat stored in an object with constant volume, J) and the T is the temperature in K.
The entransy balance equation can be obtained from the energy conservation equation for heat conduction, without heat source:

$$\rho c_P \frac{\partial T}{\partial t} = -\nabla \cdot \dot{\boldsymbol{q}} = \nabla \cdot (k\nabla T)$$

Multiplying both sides with T and writing the equation in terms of entransy:

$$\frac{\partial En}{\partial t} = \nabla \cdot (Tk\nabla T) - \dot{En}_{\phi}$$

Where the term on the left-hand side is the time variation of entransy density, the first term on the right-hand side is the entransy transfer ability due to heat transfer and the last term on the right-hand side is the entransy dissipation rate. Entransy dissipation is a key concept in the entransy analysis. In a heat transfer process, heat and entransy are transferred however entransy is dissipated (heat transfer ability is being lost). Entransy dissipation rate is defined as:

$$\dot{En}_{\phi} = k\,|\nabla T|^2 = -\dot{\boldsymbol{q}} \cdot \nabla T$$

It could be seen that the entransy dissipation is a function of the quantity of the heat transferred and the temperature difference, hence the reduction of the temperature difference within the system will result in the reduction of entransy dissipation.

Examples of the new evaluation method

Temperature-heat (T-Q) diagrams are useful to represent the thermal process and the entransy dissipation since they take into account the transferred heat and temperature levels. In Figure 2, an indoor space is being conditioned with a fan-coil unit (FCU) and a fresh air handling unit; the process in the FCU is shown in (a) and the process in fresh air handling unit is shown in (b).
In Figure 2, the areas between the lines correspond to the entransy dissipation in different components and heat transfer processes. The main idea is to decrease the temperature difference between the processes and hence decrease the total temperature difference (i.e. the task of the heat pump will decrease which will increase the COP).
In the following part, application of entransy analysis in cooling a large open space building (an airport) is shown. The first case (a) represents a conventional cooling strategy where the cold air supplied into the space and it mixes with the warm indoor air. In the second case (b), another method with radiant floor cooling and displacement ventilation is utilized. The displacement ventilation is used to condition the first 2 m of the space. The two different principles are shown in Figure 3.
In Figure 4, the shaded areas represent the entransy dissipa- ▷

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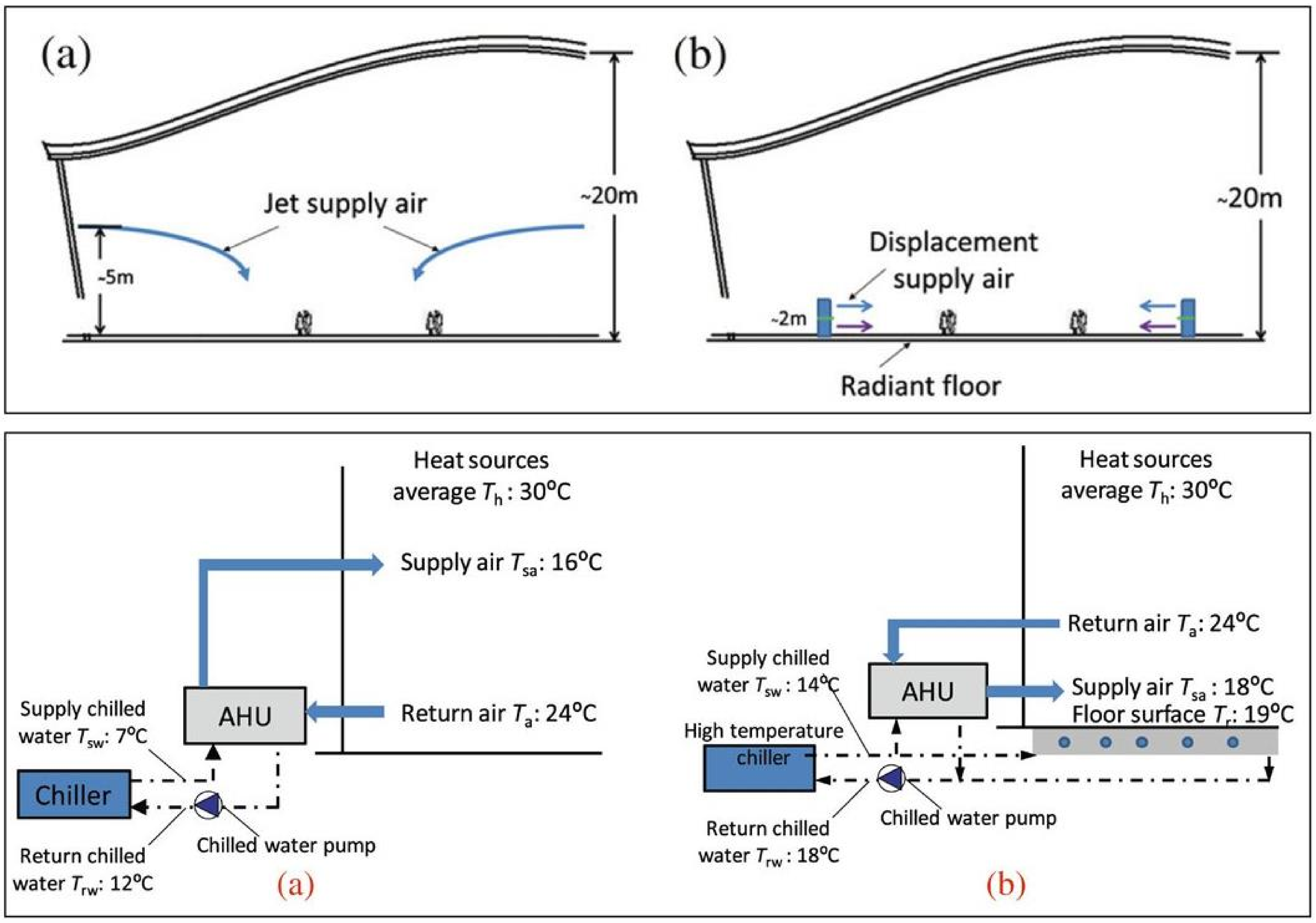

Figure 3: Two different systems for cooling a large space building (airport) (Zhang et al., 2013).

tion and it is possible to see that the second case has lower entransy dissipation than the first one.
In this case the reduced entransy dissipation indicates that the same cooling effect can be obtained with a higher chilled water temperature which indicates that the existing chillers can operate with higher efficiency or if the system were to be dimensioned from scratch, lower capacity chillers could be chosen indicating lower initial costs.

Applications within the current project

Within the current PhD project there are two main areas of the different analysis methods; the first one is a plus-energy, single family house (DTU's house for the competition Solar Decathlon Europe 2012, Fold (Kazanci et al., 2014)). Currently, all year round measurements are ongoing with different heating/cooling strategies. After the experiments, the effects of different combinations and different factors (infiltration, thermal bridges etc.) will be evaluated by energy, exergy, and entransy analyses. The house and its interior can be seen in Figure 5 and 6.
In the second part, the key parameters of different indoor terminal units (radiant systems, fan-coil units, chilled beams etc.) will be identified. The possibilities and limitations for coupling different terminal units with different heat sources/sinks will be investigated. This work will be carried parallel to IEA ECBCS Annex 59 (High Temperature Cooling and Low Temperature Heating in Buildings) which aims at finding ways of minimizing temperature differences in HVAC systems for high energy efficiency in buildings.

Expected outcomes

After all the analyses are completed, the results from energy, exergy, and entransy analyses regarding improvement and optimization in design and operation of HVAC systems will be compared. Improvement and optimization strategies based on theoretical evaluations will be proposed. These strategies will be validated with simulations, and with experiments when applicable.
The ultimate goal is to come up with validated improvement and optimization strategies for indoor terminal units (and entire HVAC system operation) ▷

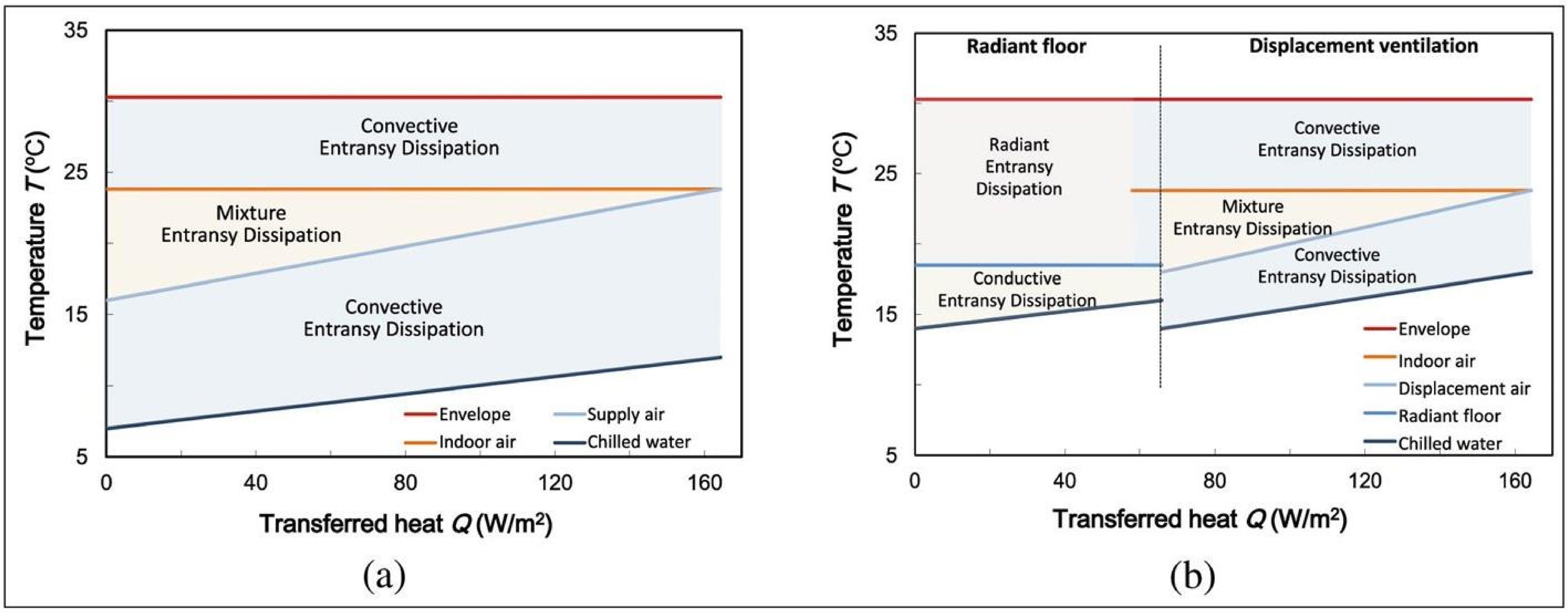

Figure 4: T-Q diagrams of the two different systems for space cooling in the airport (Zhang et al., 2013).

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Figure 5: Outside view of the test house, Fold.

Figure: 6: Inside view of the test house, Fold.